An automated procedure for deriving realistic volume conductor models for MEG/EEG source localization

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1 Introduction

The problem to find a fast, but accurate, triangulation of a subjects skin, skull and brain (SSB) for E/MEG source reconstruction is solved. The method is based on a description of volume conductor surfaces with spherical harmonic expansions and a database of exactly segmented surfaces. With the proposed procedure, relevant SSB compartments can be measured from magnetic resonance (MR) images of the head.

In addition, a method is presented to obtain an estimate of SSB surfaces when MR data is not available. For this purpose, first a surface harmonic expansion of the skin is obtained from headshape data obtained with a 3-D digitizer. Skull and brain segmentations then can be computed from a linear relationship between spherical harmonic coefficients of the skin volume and skull and brain compartments, respectively. The linear prediction model is derived from spherical harmonic expansions of the surfaces in the segmentation database.

2 Methods

2.1 Data acquisition

A database of surface segmentations was created from MR data of ten healthy control subjects, without history of neurological pathology (8 males, 2 females; age range 26-38, mean 31.1 yrs). Typically, 86 sagittal, T1-weighted, 2 mm thick MR slices were acquired (1.5T scanner, Siemens). An isotropic volume of 256^3 voxels (1 mm^3) was constructed after linear interpolation between adjacent slices. Skin, Skull and Brain surfaces were extracted from the MR cube by means of a fast 3-D region growing algorithm controlled by stopping threshold values [1], implemented in CURRY source localization software (V 3.0 Neuro Scan). The region growing procedure was controlled interactively by positioning stop markers or planes. In addition, three dimensional image operations, such as dilation or erosion were applied, e.g., for smoothing and closing the measured surface. In addition, for nine of the ten subjects, information on headshape was obtained by using the department’s MEG device as 3-D digitizer [2].

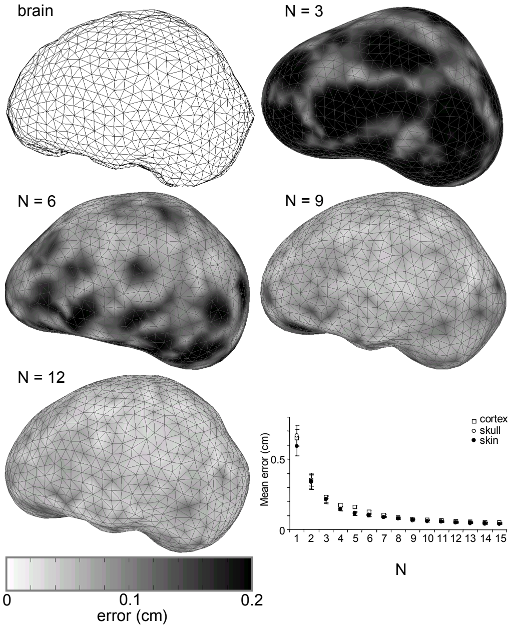

Figure 1: *Original segmentation of brain compartment for an individual subject (top left) and spherical harmonic representations of this compartment with order,* N*, increasing from 3 to 12. Gray-level maps superimposed on the compartment approximations indicate the mean radial distance (cm) between nodes on original and estimated boundaries, averaged across subjects. The bottom right panel shows mean radial distances for skin, skull and brain compartments as a function of* N.

2.2 Surface harmonics

The number of parameters necessary for describing the SSB volumes was reduced by approximating the compartments with a linear combination of surface harmonics [3, 4].

$$r(\vartheta,\varphi) = \sum_{n=0}^{N} [a_n P_n(\cos\vartheta) + \sum_{m=1}^{n} (a_{nm} \cos m\varphi + b_{nm} \sin m\varphi) P_n^m(\cos\vartheta)]$$

Here, $r(\vartheta,\varphi)$ signifies the distance, from the compartment centroid, for a node on the surface with elevation ϑ and azimuth φ. P_n and P_n^m represent the Legendre polynomials and associated Legendre functions, respectively. The order of the expansion is determined by the value of N at which the sum over n is truncated. Coefficients a_n, a_{nm} and b_{nm} are derived from a least squares fit. The number of coefficients to be estimated is given by: $N_c = (N + 1)^2$.

In the top left panel of Fig. 1, a brain compartment from the original segmentation database is shown. Spherical harmonic representations of this compartment with order N equal to 3, 6, 9 and 12 indicate that approximation of the compartment improves when N is increased. This is also evident from superimposed maps representing the mean radial distance (cm) between nodes on original and estimated boundaries, averaged across subjects. The graph in the bottom right panel shows mean distances for SSB as a function of N. In general, an adequate representation of a compartment segmentation (mean distance < 0.1 cm) is obtained when the order of the spherical harmonic expansion equals 8 or higher.

2.3 Generic model

Further data reduction was accomplished by entering the coefficients of the expansion for each subject as rows in $10 \times N_c$ coefficient matrices C^{skin}, C^{skull} and C^{brain}. Singular value decomposition (SVD) was performed on these matrices, $C=U\Sigma V^T$, with singular values sorted in ascending order, i.e., $\Sigma_1 > \Sigma_2 .... > \Sigma_{10}$. For each compartment, the rows of ΣV^T multiplied by the appropriate spherical harmonics then define a set of 10 orthogonal basis surfaces.

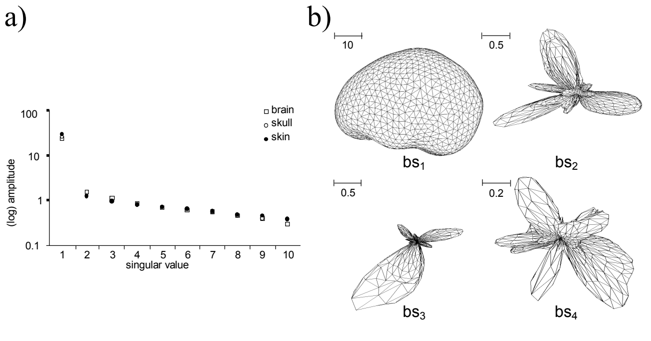

Figure 2: *a) Singular values of the SSB coefficient matrices. b) The first four basis surfaces derived from SVD of a 10 × 169 brain coefficient matrix (C^{brain}).*

Singular values of the SSB coefficient matrices are depicted in Fig. 2a. For each compartment, the first singular value is most pronounced. Amplitudes decrease slowly for subsequent values. The first four basis surfaces $bs_1..bs_4$ derived from a brain coefficient matrix with 169 spherical harmonics (N = 12) are depicted in Fig. 2b. Volume bs_1 resembles the average brain. Subsequent volumes are much smaller (note differences in scale) and have no clear physiological meaning.

2.4 Model based surface extraction

After obtaining the basis volumes, a new segmentation can be derived by, manually, delineating a compartment of interest in a number of MR slices and fitting a linear combination of the basis surfaces to the obtained data points (Fig. 3).

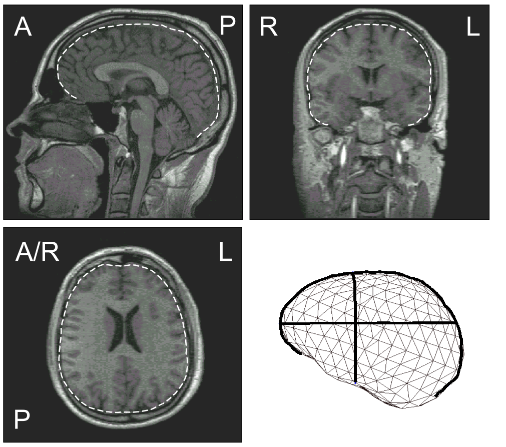

Figure 3: *The procedure for measuring a surface from MR data is illustrated for the brain compartment. The compartment of interest is delineated manually on single MR slices in sagittal, coronal and axial planes. Surface points, about 1mm equidistant, are sampled from each sketch and combined to form a 3-D contour for the surface of interest. After transforming the obtained data points to a head-fixed coordinate system (nasion-ear system), a linear combination of the predefined basis surfaces are fitted to the points by means of a linear least squares procedure (bottom right).*

2.5 Linear prediction of skull and brain

Surfaces also can be measured by fitting skin basis volumes to headshape data. Skull and brain then can be obtained using a linear regression model describing the relation between corresponding spherical harmonic coefficients of the skin, c^{skin}, and skull or brain, $c^{skull/brain}$, derived from the spherical harmonic approximations of the database of exactly segmented surfaces (Fig. 4):

$$c_m^{skull/brain} = \gamma_m c^{skin} + \delta_m$$

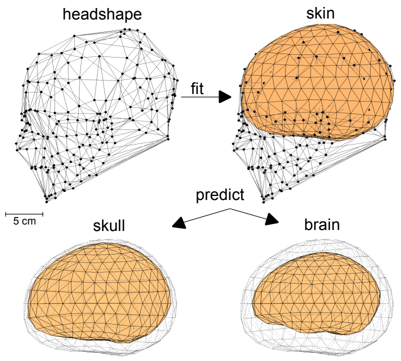

Figure 4: *Extraction of scalp, skull and brain from headshape data.*

3 Results

3.1 Segmentation from MR data

The method was tested by means of a jack-knife based procedure. SSB segmentations for each subject in the database were computed with a model based on the remaining 9 subjects. Thus, for each segmentation, 9 basis surfaces were available to approximate the compartments.

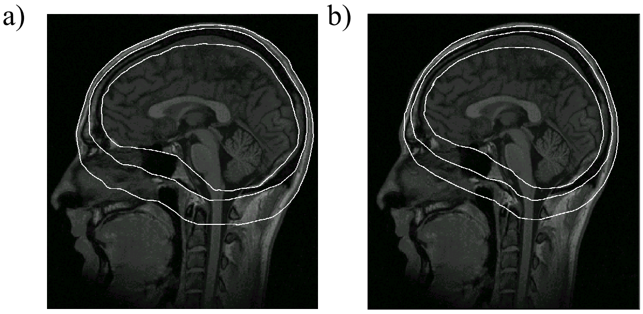

Figure 5. *SSB surfaces derived with the proposed procedure using MR data (a) or headshape data from a 3-D digitizer (b).*

Fig. 5a shows skin, skull and brain obtained with the model for one of the subjects, superimposed on a sagittal MR slice. Segmentations, using all 9 basis surfaces, describe the relevant compartments adequately. In Fig. 6, mean distances between model based surface extractions and original segmentations obtained with region growing are indicated as a function of the number of basis volumes used. Surface description improves when the second basis surface is added. Using three or more basis surfaces gives only marginal improvement. The figure shows in addition that mean distances are smaller when only the upper parts of the compartments are taken into account ($Z > Z_c$).

Fig. 7 shows spherical harmonic representations, N = 12, of SSB compartments, averaged across subjects. Gray-level maps on the left panels indicate mean radial distances (cm) between nodes of the original segmentations and boundaries measured with the model using 9 basis surfaces. For each compartment, errors less than 2 mm are evident across large parts of the surfaces. Highest errors (dark areas) are evident on the bottom regions of the compartments.

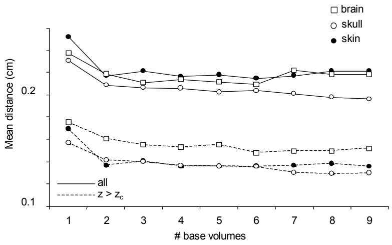

Figure 6. *Mean distance between original and model based surface extractions as a function of the number of basis volumes used; across all points and for points above the centroid of the surface nodes, only ($Z > Z_c$: dashed).*

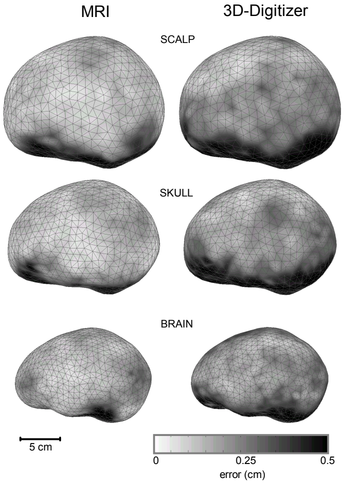

Figure 7. *Spherical harmonic representations, N = 12, of SSB compartments. Gray-level maps indicate the mean radial distance (cm) between nodes on the original segmentations and boundaries measured with the model, either using MR data (left) or 3-D digitized headshape data.*

3.2 Segmentation from headshape

In Fig. 5b, skin, skull and brain compartments are shown obtained with the model applied on 3-D digitized headshape data. Segmentations closely resemble the surfaces obtained with the model applied on MR images (Fig. 5a). The right panels of Fig. 7 indicate mean radial distances (cm) between nodes of the original segmentations and boundaries measured with the model using headshape. For each compartment, mean distances are somewhat larger (about 1mm) compared with segmentations from the model performed on MR data. Again errors are highest on the bottom regions of the compartments.

4 Discussion

With the proposed method, SSB surfaces are obtained highly comparable to segmentations obtained with a 3-D region growing algorithm. The method is much less time consuming compared with region-growing, requiring the interactive setting of graylevel thresholds and stopping markers to optimize discrimination between adjacent head compartments (model × 10 minutes; region growing > 60 minutes). The method also can be used for deriving realistic volume conductor models when anatomical data is not available.

References

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